Effect of Acoustic Excitation on Ammonium Perchlorate Decomposition and Combustion

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1 Abstract

The experimental study on the combustion decomposition of ammonium perchlorate (AP) particles under different external acoustic excitation is carried out with a methane planar burner. The results show that the decomposition time, average maximum amplitude, self-excitation amplitude and oscillation amplitude of AP combustion are influenced by the frequency and amplitude of external acoustic excitation. Low-frequency and medium-amplitude external excitation conditions can accelerate the combustion decomposition of AP and shorten the decomposition combustion time, but it is easy to cause additional higher amplitude of acoustic pressure oscillation. The combustion and decomposition process of AP will attenuate the amplitude corresponding to the external excitation, and the attenuation is positively correlated with the excitation amplitude.

2 Introduction

In recent years, combustion instability occurs frequently in solid rocket motors. One of the main reason is the coupling of acoustic and combustion process in solid rocket motors [1]. In solid composite propellants, ammonium perchlorate (AP) is widely used as an oxidant with a high mass ratio[2]. Studies have shown that pressure oscillation have an effect on decomposition and combustion of AP [3]. The evaporation process of liquid fuel droplets will be affected by pressure waves and generate a response. It is easy to excite acoustic instability at high pressure and low frequency in liquid fuel[4]. The decomposition and combustion process of AP has a transmitting process from solid phase to liquid phase to gas phase [5.] The decomposition and combustion of AP not only generates acoustic pressure, but also its decomposition and evaporation are affected by acoustic pressure oscillation. It is necessary to study the response of AP to the combustion process under external acoustic excitation.

3 Experimental setup and condition

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This experimental setup is shown in Figure 1, which is mainly composed of methane premix flame burner system, gas supply system, acoustic excitation and acquisition system, temperature acquisition system, ammonium perchlorate particle supply device, and video camera. The gas supply system includes three kinds of gas (methane, nitrogen and oxygen) high-pressure gas storage cylinder, flow controller (Type： D08-2f, range of 500mL, 5L and 2L respectively), reversing valve and stainless steel tube (inner diameter of 4mm), etc. The acoustic excitation and acquisition system is composed of low frequency signal generator (Tektronix arbitrary function signal generator AFG/3011C), low-frequency loudspeaker (3 ohm 4W), acoustic pressure sensor and computer acquisition software. The temperature acquisition device is consisted of platinum-rhodium thermocouple (S-type, 0.5mm in diameter) and multi-channel data recorder. Ammonium perchlorate feeding device is mainly composed of electronic balance (accuracy 0.1mg), medicine spoon and funnel and shown in Figure 1. The methane premix flame burner is mainly composed of quartz glass tube, stainless steel tube, metal joints, porous media, sealing gasket and other components. The combustion tube is made of quartz glass tube, 150mm long, 10mm inside diameter and 1mm wall thickness. The glass tube is filled with porous medium material a thickness of 30mm is nickel foam (75ppi), and the bottom end of the. A 100mm length t-shaped stainless steel tube with inner diameter 10mm is processed in the middle position for placing acoustic pressure sensor.

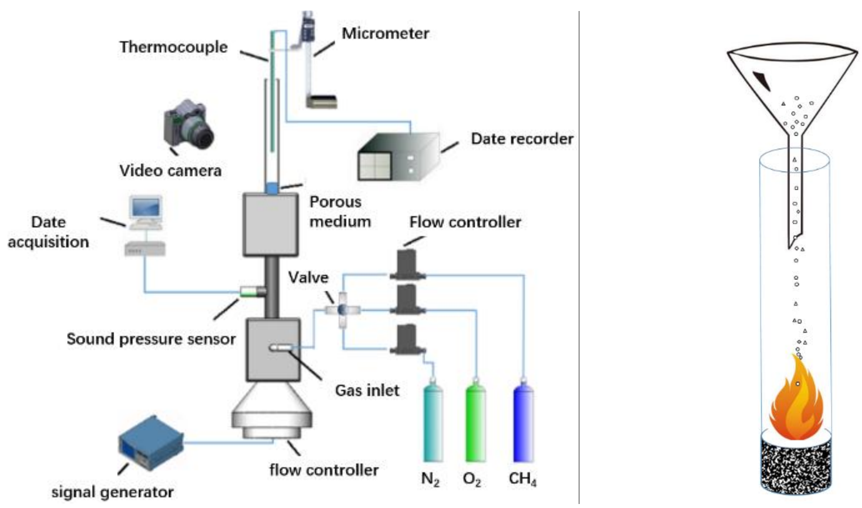

Figure 1. Experimental setup

The gas temperature in the burner is measured by platinum-rhodium thermocouple. Ammonium perchlorate particles combustion flame is recorded by Phantom video camera with 300 frames. The acoustic pressure generated by the combustion of ammonium perchlorate particles is measured by acoustic pressure sensor (BSWA MPA416) mounted in the middle of the stainless steel tube. The acoustic pressure data was collected by the NI cDAQ-9171 data acquisition card and finally transmitted to the computer for processing and analyzing. The sampling frequency of the acquisition card is 50KHz and the sampling time last for 3 seconds. The loudspeaker connected to the signal generator provides external acoustic excitation for the burner. By adjusting the input voltage and frequency of the signal generator, the amplitude and frequency of the acoustic excitation emitted by the loudspeaker can be adjusted. After the flame and the external acoustic excitation are stabilized, the weighed AP particles are uniformly poured into the burner from quartz tube outlet, and fall onto the porous medium surface. After being heated by the premixed flame, AP particles are decomposed and burned. In the experiment, ammonium perchlorate particles with an average particle size distribution of 80-120 μm were used, with a purity of 99.5%, a density of 1.95 g/cm^3 and a brittleness

I class. Acoustic pressure sensor is used to obtain data in the process of heat decomposition and combustion of AP particles after heating, and camera was used to record the test process.

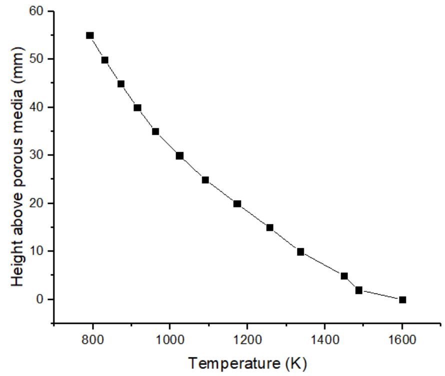

Figure 2 Temperature distribution in tube

AP particles melting point is about 623k in solid rocket propellant combustion, the combustion surface near the AP in the decomposition of the combustion environment has been significantly higher than the melting point of AP, by controlling the flat flame burner premixed gas equivalent ratio to reach an enough high temperature. The experiment is carried out under the combustion environment of methane premixed gas with the equivalent ratio of 1.0. In the premixed gas, methane is 0.134L/min, oxygen flow is 0.26 L/min, and nitrogen is 1.01 L/min. The temperature distribution along the axis of above the porous medium in the burner is higher than 800K. The maximum measured temperature on the surface of the porous medium is about 1600K. Considering the influence of radiation and heat transfer of the thermocouple, the actual temperature should be higher than 1600K.

From the thermoacoustic vibration frequency formula: $F = c/(2 * L)$, we can obtained characteristic frequency of burner tube. Where F is the characteristic frequency, the length of burner tube L=360mm, the specific heat ratio k=1.22 and gas constant R=286J/kg k, and the natural acoustic frequency of burner oscillation is 1295Hz, which is close to the high-frequency oscillation frequency 1250.4Hz measured in the later experiment.

4 Results and Discussions

AP is rapidly decompose in the burner with bright flame and accompanied by an obvious acoustic oscillation signal. Figure 3 is the pictures of AP combustion process. After AP particles falling onto burner, it is only need about 0.33s to reach the most brightness flame zone, about 0.50s is cost in the flame darken process.

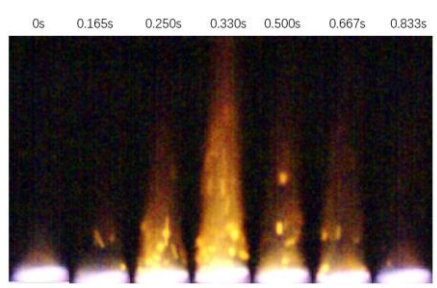

Figure. 3 Pictures of AP combustion process

Figure 4 shows the comparison of acoustic pressure data collected in the process of AP combustion decomposition under the condition of no external acoustic excitation and external acoustic excitation (100Hz, 5Pa) . Since we focus on acoustic pressure of AP combustion characteristics, as shown in figure 4 we define maximum acoustic pressure as Max Peak Amplitude, the negative maximum acoustic pressure as Min Peak Amplitude, Min and Max Peak Average for Average Maximum Amplitude. The time for AP complete combustion process through as the yellow area is defined as Combustion Time.

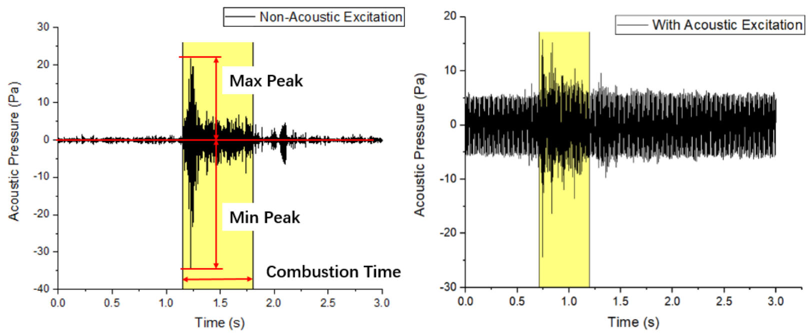

Figure 4 Comparison of AP acoustic pressure

The two groups of data in the figure 4 shows that the positive maximum amplitude of acoustic pressure without external acoustic excitation is 21.85pa, the negative maximum amplitude is -34.196Pa, the combustion time is 0.6507s, the positive maximum amplitude of acoustic pressure under external acoustic excitation (100Hz, 5Pa) is 15.77Pa, the negative maximum amplitude is -24.41Pa, and combustion time is 0.5492s. It can be seen that under the condition of the external acoustic excitation (100Hz, 5Pa), Max Amplitude and Combustion Time are significantly different. Analyzing experimental data of pressure oscillation with Fast Fourier Transfer, the result of figure 5 shows that the maximum amplitude of acoustic pressure for external acoustic excitation frequency of 100 Hz, induces four new acoustic pressure oscillation, the acoustic pressure oscillation frequency is 422 (1st), 1033 (2nd), 1250 (3rd), 1644Hz (4th) respectively.

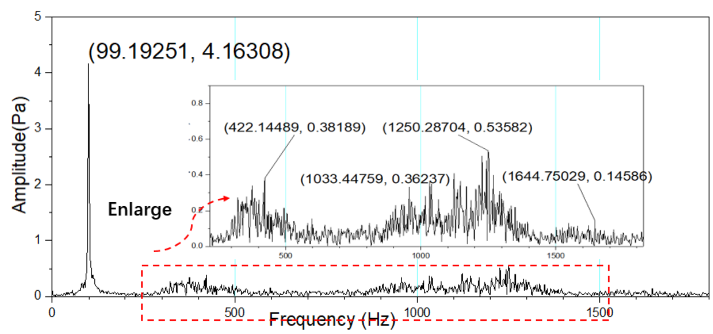

Figure 5 Acoustic pressure oscillation with Fast Fourier Transfer

It shows that the combustion decomposition process of AP will generate acoustic pressure oscillation. This section mainly studies the interaction between the external acoustic excitation and the acoustic pressure oscillation generated by the combustion decomposition of AP. By adjusting the input voltage and frequency of the loudspeaker to change the amplitude and frequency of the external acoustic excitation, the influence of the amplitude and frequency of different external acoustic excitation on the acoustic pressure oscillation characteristics of AP combustion decomposition is studied. All subsequent experiments were conducted repeatly and the experimental results were statistically averaged.

4.1 Effect of excitation amplitude on AP combustion response

Through the data collected in the experiment, the data of combustion time, average maximum amplitude, self-excitation amplitude and oscillation amplitude under different excitation frequencies were obtained after data processing. Figure 6 is comparison of AP combustion time with and without external acoustic excitation in the burner. Under the condition of without external acoustic excitation, AP combustion time is 0.7167s and the average maximum amplitude is 23.83Pa.

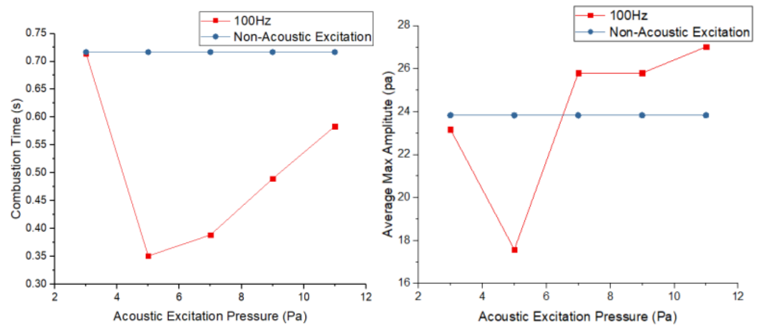

Figure 6 Excitation amplitude vs combustion time and max amplitude

As the increase of external acoustic excitation pressure, the combustion time decreased from 0.7143 s to 0.3506s and then gradually increased to 0.5835s. The external acoustic excitation at 3Pa is almost the same as that at the condition of without excitation, indicating that the external excitation at a lower frequency and a lower amplitude has almost no effect on AP combustion time. With the increase of excitation amplitude at 100Hz, the average maximum amplitude gradually increases after decreasing from the initial 23.83Pa to 17.57Pa. External excitation pressure oscillation ampitude may affected by the decomposition of AP combustion. We define the self-excitation amplitude as amplitude of corresponding to acoustic excitation frequency. Data from figure 7 shows that under the condition of the same excitation frequency, with the increase of excitation amplitude, self excitation amplitude will be reduced relative to without exictation, and the difference gradually increased. This indicates that the AP combustion decomposition process will attenuate the amplitude corresponding to the external excitation, and the intensity of attenuation is positively correlated with excitation amplitude.

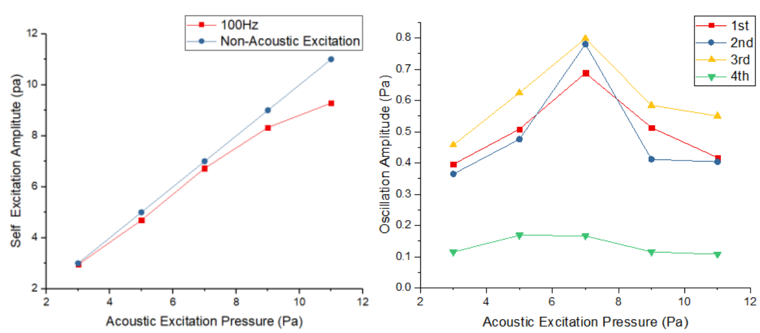

Figure 7 Excitation amplitude vs. self-excitation and oscillation amplitude

The oscillation amplitude is corresponding to the four newly excited acoustic pressure oscillation frequencies under the condition of 100Hz, and each oscillation amplitude first increases and then decreases. The amplitude of 3rd is higher than that of other oscillation frequencies, and 4th is obviously lower than that of other oscillation frequencies. It is shown that more energy introduced by AP combustion is used to excite 900-1300Hz acoustic pressure oscillation.

4.2 Effect of excitation frequency on AP combustion response

From the analysis in the previous section, it can be seen that 5Pa under 100Hz acoustic excitation corresponding to combustion time and the oscillation amplitudes are all extreme values. The purpose of this section is to study the influence of the excited combustion frequency on the combustion response, so it is necessary to keep the excitation amplitude constant and study the influence of the excited frequency on the combustion response by changing the acoustic excitation frequency.

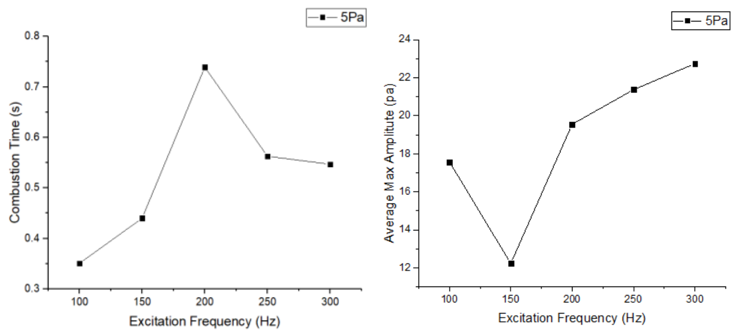

Fig 7 Excitation frequency vs combustion time and max amplitude

The combustion time changing with excitation frequency is completely opposite to that with excitation amplitude. Under the condition of 5Pa excitation amplitude, combustion time gradually increases from 0.3507s to 0.7391s of 200Hz, and then decreases to 0.5469s as the excitation frequency increases from 100Hz to 300Hz. With the increase of excitation frequency, the average maximum amplitude first decreases and then increases from 17.57Pa to 22.74Pa, and 12.23Pa is the minimum value. The results show that under the same amplitude, the smaller excitation frequency will accelerate the combustion decomposition of AP, thus shortening the decomposition combustion time. The instantaneous released energy is higher, which leads to a higher average maximum amplitude and short reaction time.

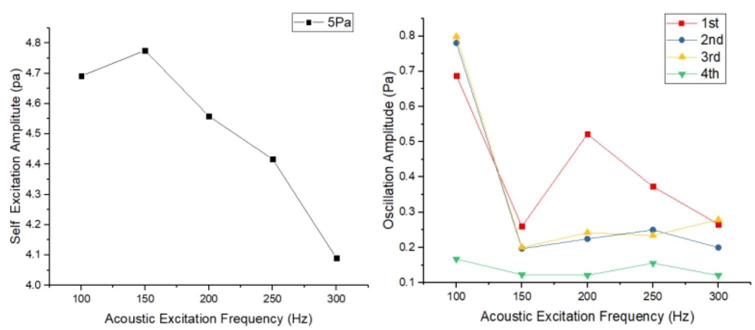

Fig 8 Excitation frequency vs self-excitation and oscillation amplitude

As the increase of excitation frequency, the self-excitation amplitude increased slightly from 4.69Pa to 4.78Pa and then decreased to 4.09Pa. The oscillation amplitudes corresponding to 422Hz (1st), 1033Hz (2nd), and 1250Hz (3rd) contain majority energy introduced by the combustion of AP. The oscillation amplitude of 1644Hz (4th) is almost unchanged at a lower level. The results show that the oscillation amplitude excited at 100Hz is much higher than other higher frequencies, and the low frequency excitation is easy to cause new extra oscillation.

5 Conclusions

1. Both the frequency and amplitude of external acoustic excitation will affect the decomposition time, average maximum amplitude, self-excitation amplitude and oscillation amplitude of AP combustion.

2. External excitation with low amplitude has almost no influence on AP combustion time. AP combustion decomposition process will attenuate the amplitude corresponding to the external excitation, and the intensity of the attenuation is positively correlated with the excitation amplitude. The oscillation amplitudes corresponding to new excited oscillation frequencies are first increased and then decreased

3. Low frequency excitation will shorten the decomposition combustion time, and lead to a higher average maximum amplitude. The attenuation ability of the acoustic pressure generated by AP combustion to the external acoustic excitation amplitude increases with the increase of the external excitation frequency.

4. Low-frequency and medium-amplitude of external excitation can accelerate the decomposition and combustion of AP and shorten the combustion time, but it is easy to cause new acoustic pressure oscillation.

References

[1] Blomshield F S . Lessons Learned In Solid Rocket Combustion Instability [J]. 2013.

[2] Boldyrev V V , Alexandrov V V , Boldyreva A V , et al. On the mechanism of the thermal decomposition of ammonium perchlorate [J]. Combustion & Flame, 1970, 15(1):71-77.

[3] Strunin V A , Mandelis G B . The effect of pressure on the kinetics of thermal decomposition of ammonium perchlorate [J]. Bulletin of the Academy of Sciences of the Ussr Division of Chemical Science, 1964, 13(12):2127-2128.

[4] Lee G Y , Kim S Y , Yoon W S . Oscillatory vaporization and acoustic response of droplet at high pressure [J]. International Communications in Heat and Mass Transfer, 2008, 35(10):1302-1306.

[5] Siegmund R F. Kinetics of the thermal decomposition of perchlorate [D]. University of Miami, 1970.